Heavy-Ion Virtual National Laboratory*

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Heavy Ion Fusion Virtual National Laboratory

Presented to:
OFES Budget Planning meeting
March 13-15, 2001

- Goals/Scientific Issues
- Strategy/Funding
- Organization
- Experiments/Progress (Simulations/Theory by Ed Lee)
- Plans

☞ **The Heavy-Ion-Fusion (HIF) Program's long range goal is to provide comprehensive scientific knowledge for inertial fusion energy (IFE) driven by high-brightness heavy-ion beams**

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC03-76SF00098 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

Goal of HIF-VNL science: explore limits to beam brightness that lead to lowest energy to drive targets

- To ignite a target requires a typical beam intensity S ~10^{14} to 10^{15} W/cm^2 and specific energy deposition ~ 10^8 J/gm. Driver energy E generally decreases strongly with focal spot size r_f, e.g., $E \sim r_f^3$. (Lindl talk)

- An ion bunch (as neutral or nonneutral plasma) must be compressed to a small volume against its thermal pressure and space-charge forces. The space charge forces may be reduced with plasma neutralization.

- Through advanced diagnostics, beam control algorithms, optimized focusing systems, innovative target designs, and good plasma neutralization of beam space charge in the target chamber, we may learn how to achieve smaller focal spots leading to potential reductions in ion kinetic energy and driver energy by 10 to 100X : E.g.,
  - Focal spot size: rf ~ 2.5 mm → 1 mm or less
  - Ion kinetic energy: T ~ 10 GeV → 1 GeV or less
  - Total beam energy: E ~ 10 MJ → 1 MJ or less
  - "Conservative" → "Potential"

To achieve potential reductions in driver energy, we must preserve source brightness through acceleration and focusing

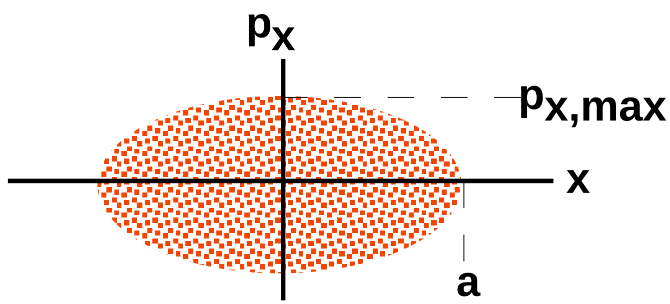
- Beam brightness (phase space density) $\mathcal{B}$ is the current density per unit solid angle. Intensity on target S increases with brightness.

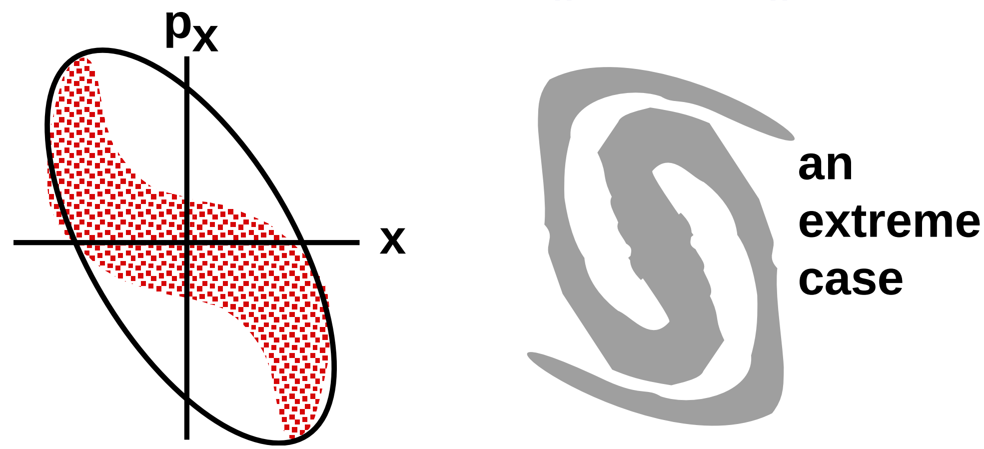
- The Vlasov equation $\Rightarrow$ normalized brightness $\mathcal{B}_n = \mathcal{B} / (\beta\gamma)^2$ is conserved for constant pulse durations (Liouville's Theorem).

- Sources have shown brightness $\mathcal{B}_n$ orders of magnitude larger than needed for $S=10^{15}$ W/cm^2 at $\Omega/4\pi \approx 1\%$ and T ~ 10GeV. Thus, $S\sim10^{15}$ W/cm^2 at T < 1 GeV is in principle possible, and at focal spots r_f < 1mm, if space charge can be neutralized.

- Low current scaled experiments (SBTE) showed preservation of beam brightness transported over 80 quadrupoles. →We propose to study the evolution of beam brightness with transport at ampere-level currents, and later with acceleration and focusing, in the High Current Experiment (HCX) series.

Emittance concept and a typical diagnostic for the beam particle distribution function F(x,p,t)→measures brightness $\mathcal{B}_n \sim I/\pi^2 \varepsilon_n^2$

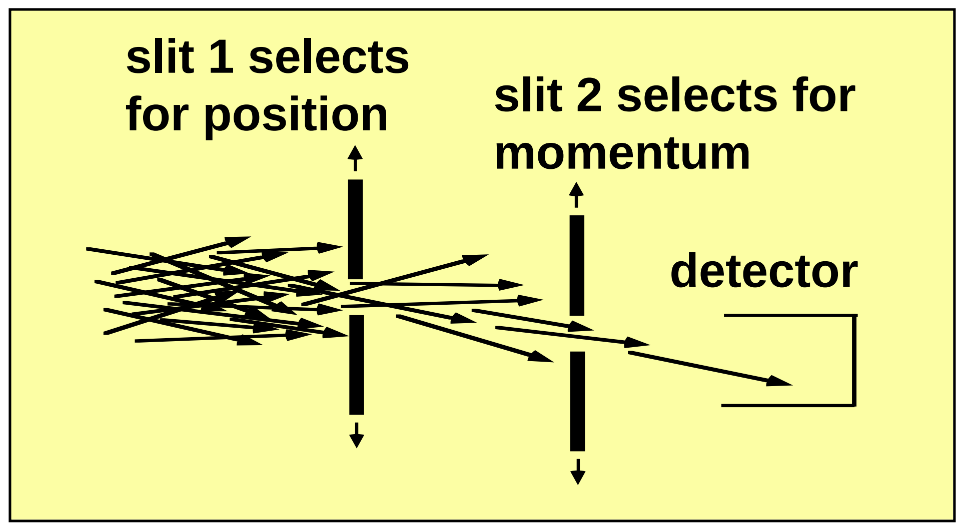




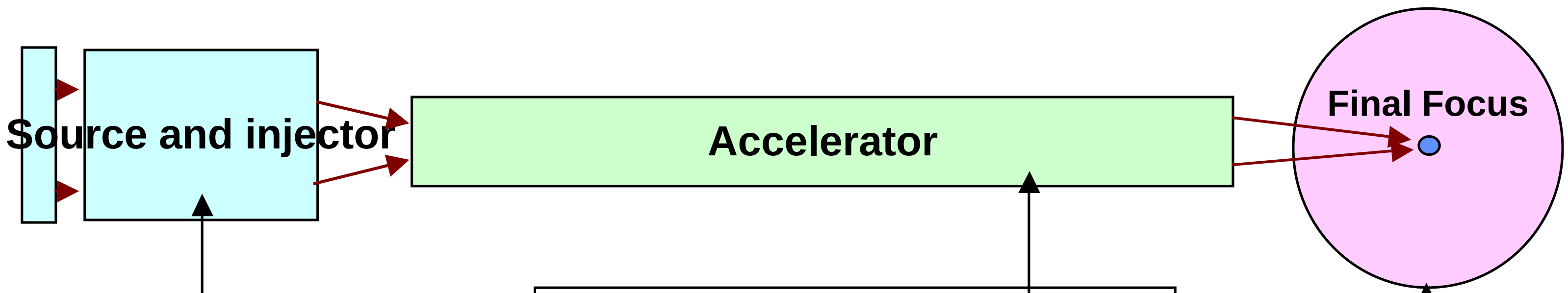
F(x,p,t) gives beam brightness, emittance, and everything else. Microscopic 6D density is always conserved (Liouville's theorem)

In an ideal accelerator (forces linear in x, y, z) the macroscopic normalized emittance $\varepsilon_N = a\, p_{x,max}/p_z$ is conserved

Nonlinear applied and space-charge fields lead to distortion of phase space



HIF Scientific Issues



What physics determines beam brightness in heavy-ion sources and low energy transport?

What dynamical phenomena affect the quality of space-charge-dominated beams undergoing transport and acceleration?

What role do non-linear processes and beam-plasma interaction play in beam chamber propagation and focusing onto a target?

How can we best apply and improve computational tools to provide the needed support for experiments, exploration of issues, and planning for the future?

(Ed Lee to address theory/simulation in this review)

The IRE remains a necessary step for HIF, but our near term strategy is to expand scientific capability in our existing facilities to study beam brightness evolution

☞ **Near-term base (next 2 years +): High current experiments (HCX) and simulations for sources, beam transport with electrostatic and magnetic quadrupoles, and focusing**

→Requires at least flat VNL funding of $10.6 M/yr.

☞ **Near-term (2- 5 years): Add 5 to 20 MeV acceleration capability to HCX, to allow integrated beam drift compression and final focusing experiments**

→ Requires increased HIF-VNL funding to $16 M/yr

☞ **Medium-Term (5- 10 years): Higher energy (30-300 kJ, 200-400 MeV) Integrated Research Experiment (IRE) to study non-ignited HIF-specific target physics and multiple beam effects**

→ Requires ~ $80-120 M/yr

☞ **Long-Term (15-20 years): ETF tests of driver, final focus and chamber with > 100 MJ yield @ 5 Hz → fully-integrated IFE experiments,**

→ Requires ~$2B total construction

The U.S. HIF Virtual National Laboratory

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Heavy Ion Fusion- PPPL

Objectives

- Develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense heavy ion beams propagating in periodic focusing accelerators and transport systems, and on beam-plasma interactions in the target chamber.

- Carry out experimental studies of intense ion beam propagation and beam-plasma interactions in the target chamber in high-leverage areas that make effective use of PPPL's established experimental capabilities.

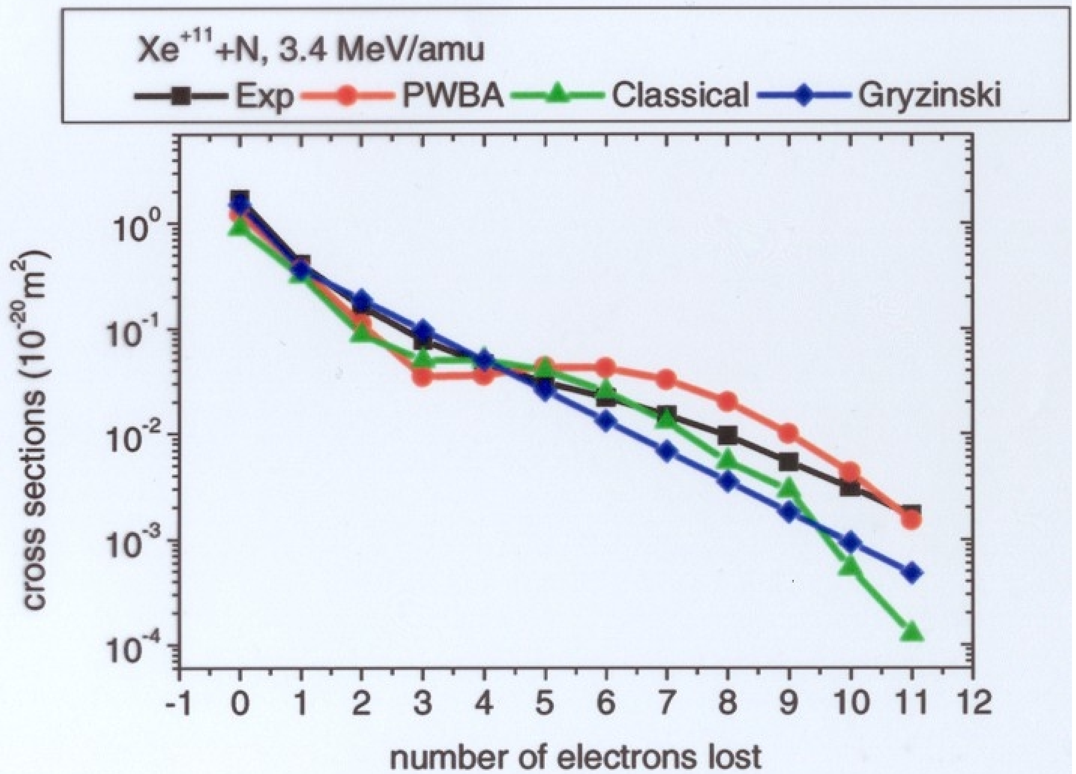
- Carry out engineering design studies in selected high-leverage areas, e.g., final focus magnets and nonlinear beam optics, and target chamber interface.

Personnel

R. C. Davidson, P. Efthimion, L. Grisham, P. Heitzenroeder, C. Jun, I. Kaganovich, R. Kolesnikov, W. W. Lee, D. Mueller, H. Qin, E. Startsev, S. Strasburg and S. Tzenov.

Multielectron Losses Cross Sections in Xe

- Average cross-sections for electron loss from 3.4 MeV/m Xe^{11+} in N_2 per one nitrogen atom determined from the data taken at cell pressures ≤ 8 mTorr.



University of Maryland HIF Experiments and Simulations

WARP study of equipartitioning in HIF-scale beams.

Experiment underway on growth of energy spread.

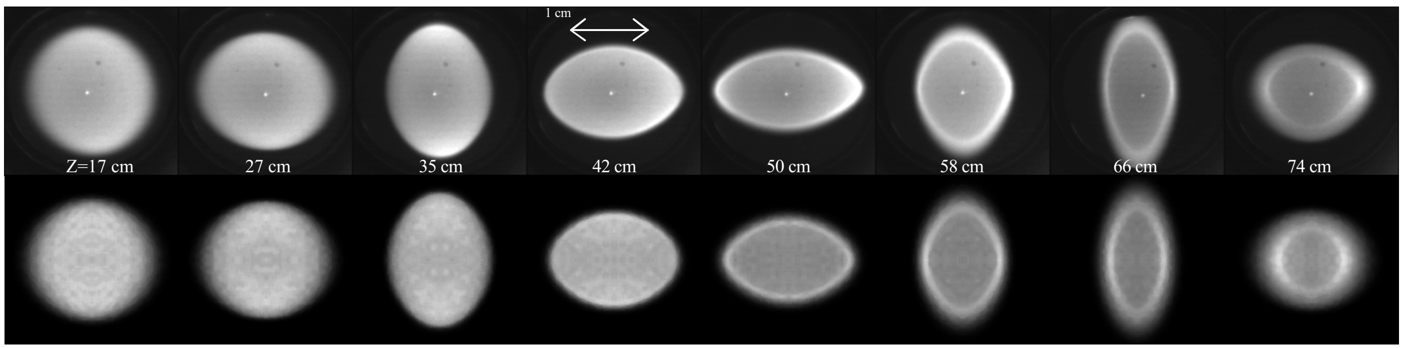
Benchmarking of WARP code against ongoing experiments, including results from University of Maryland Electron Ring (UMER).

Designed several experiments to be implemented on UMER during installation and compared against existing simulation work:

- Introducing anisotropy to study equipartitioning. (next 6 months)
- Studying effects of skew quadrupoles, and introducing beam-based correction to skew quad errors. (next 6-18 months)
- Exploring collimation and wave propagation over long-scale lengths. (next 12 months)

Experiment

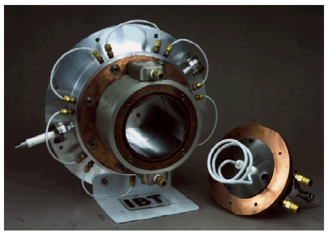
WARP Simulation

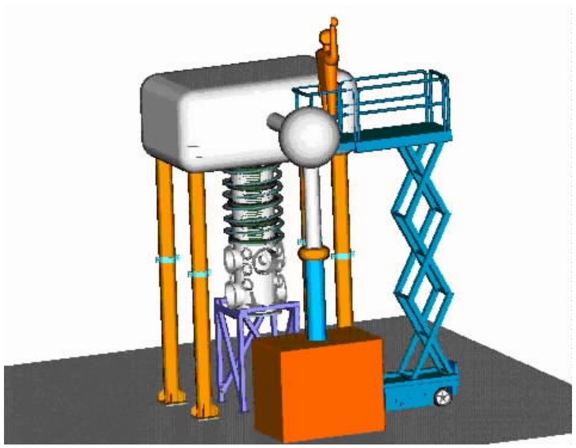


We will explore a novel "merging beamlet" injector concept to increase source brightness for HCX and IRE

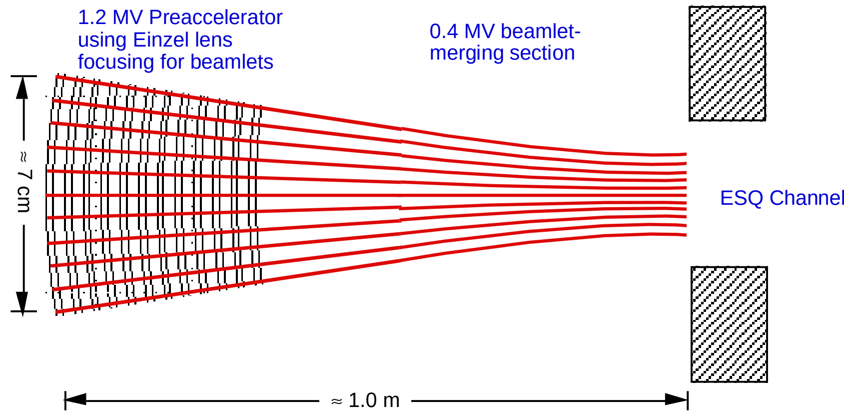
Child-Langmuir: $J_{CL} \propto \frac{V^{3/2}}{d^2}$ **and** $V \propto d^{0.5\ to\ 1.0}$

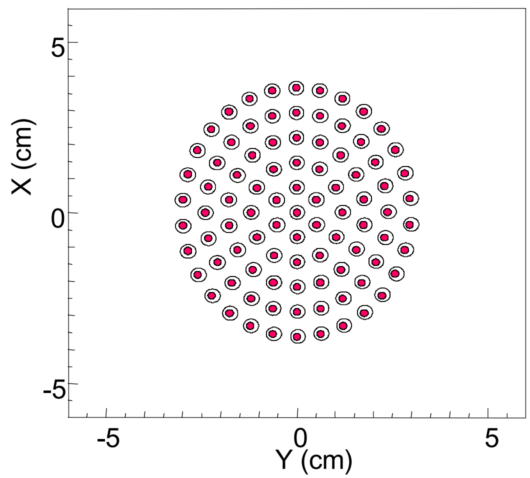
$\Rightarrow$ **small multi-aperture sources.**

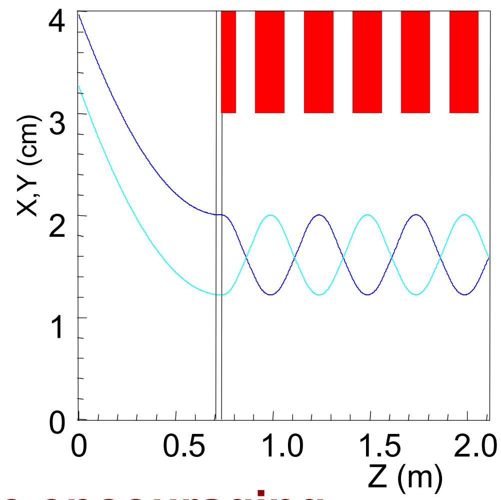




500 kV ion source test stand at LLNL is under construction





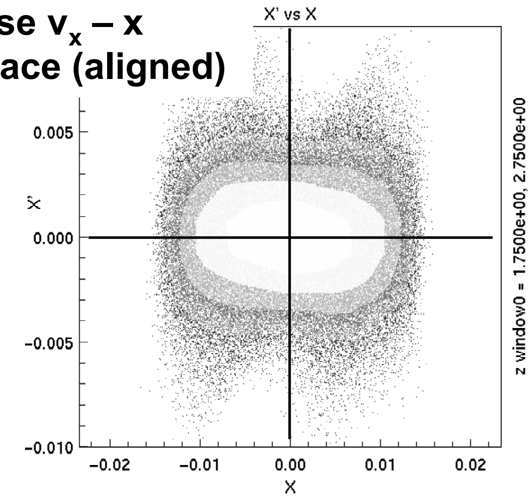


Simulation results are encouraging

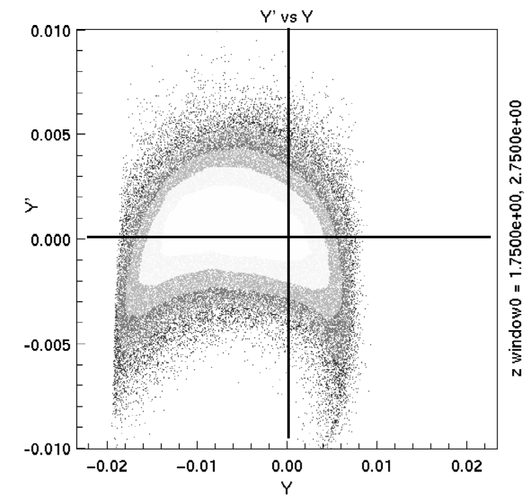
HCX phase 1 will quantify the brightness evolution of a driver scale beam

- --Through 40 electrostatic quadrupoles (six plasma oscillations).
- Approach: induce phase space distortions, seed halo formation via quadrupole offsets, lattice perturbations.
- --Additional 4 magnetic quadrupoles.
- Approach: Secondary e^- effects; explore differences from electrostatic quads.
- Use as test bed for diagnostics development.
  - –Non-intercepting diagnostics
- Explore longitudinal bunch control.

Transverse v_x – x phase space (aligned)



Offset in y → leads to centroid oscillation/phase space distortions.



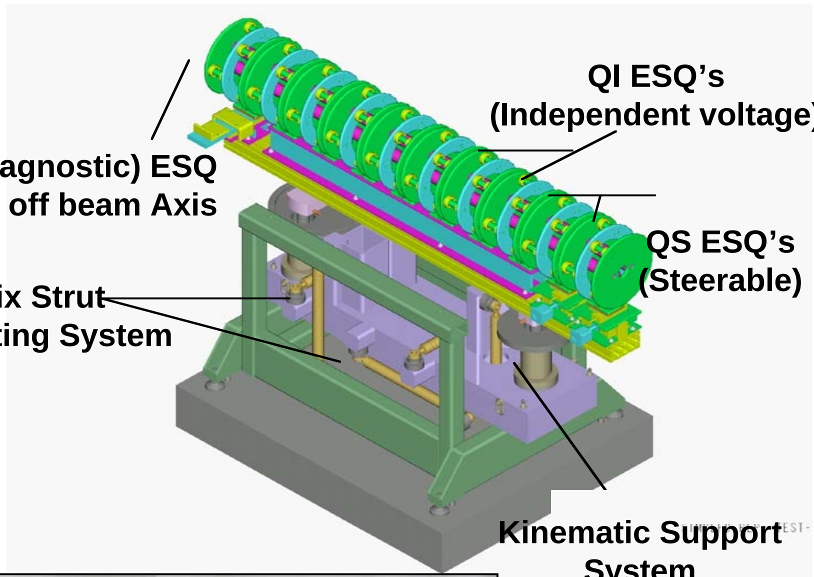
HCX (Phase I): Maximize <J>, beam brightness

What dynamical phenomena affect the quality of space-charge-dominated beams undergoing transport and acceleration?

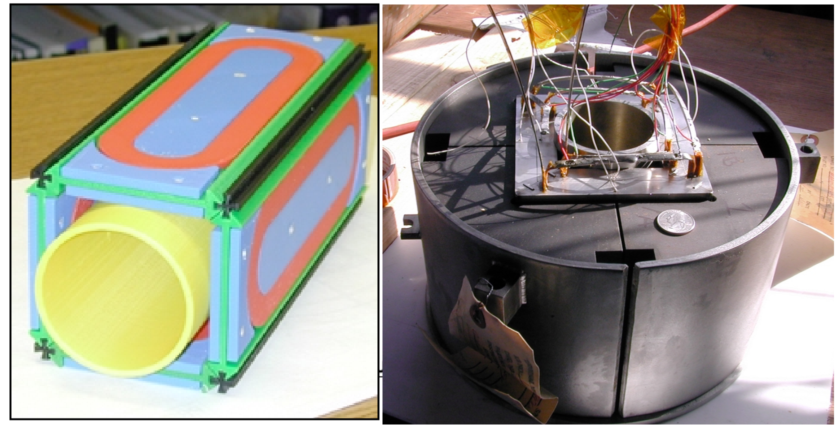
- Beam transport stability limits.
- Focusing field imperfections and beam induced images.
- Halo formation.
- Desorption of gas from transport channel walls.
- Beam perturbations due to secondary electrons.
- Beam background-gas interactions.
- Transport quadrupole design.
- Diagnostic sensitivity and beam control accuracy.

These are topics of great interest in high intensity accelerator and beam physics, and have enormous impact on scale and cost of future scientific research as well as heavy-ion drivers for IFE

We are installing the first 10 Electric quadrupoles in HCX First beam: This Year

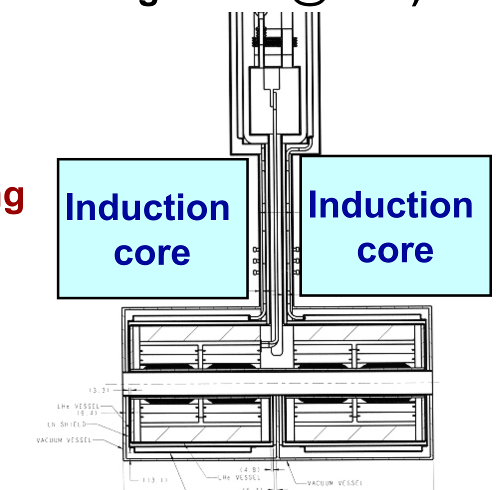


We are developing enabling technology for HCX

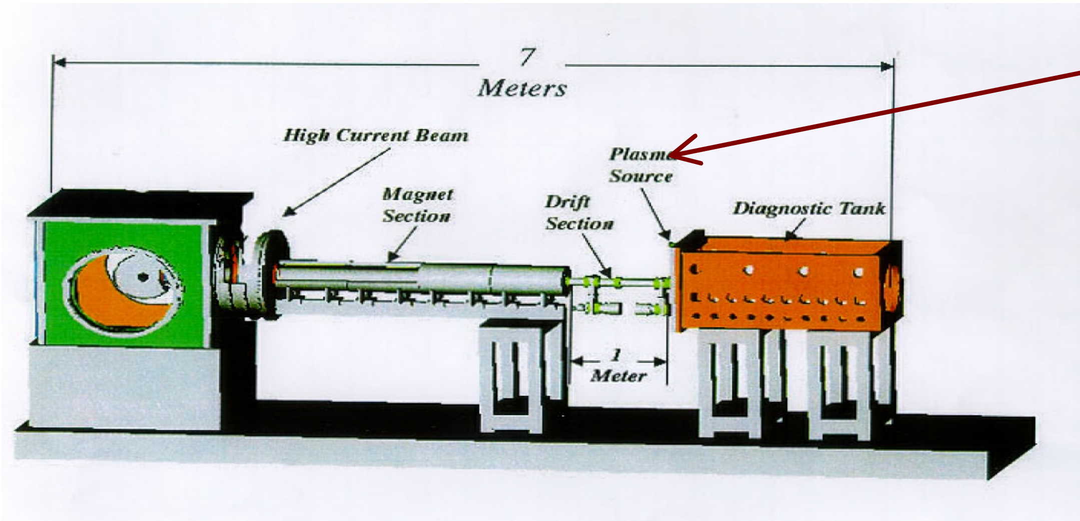


N. Martovetsky (LLNL) prototype SC magnetic quad. Good preliminary test results. (Advanced Magnet Lab prototype is being tested @ MIT.)

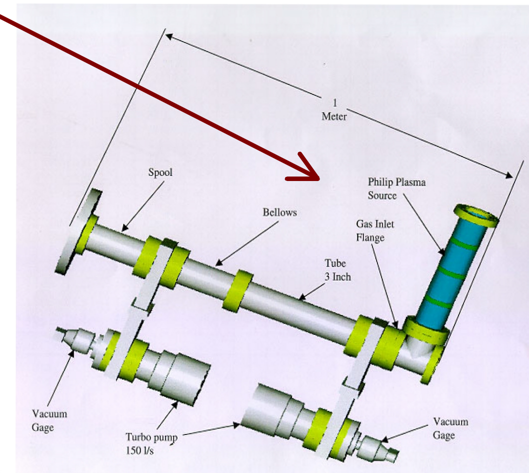
These superconducting magnetic quads are compact enough to allow induction acceleration cores to be added to HCX



A high current (~ 100 mA) experiment is being designed to study ballistic focus with plasma neutralization

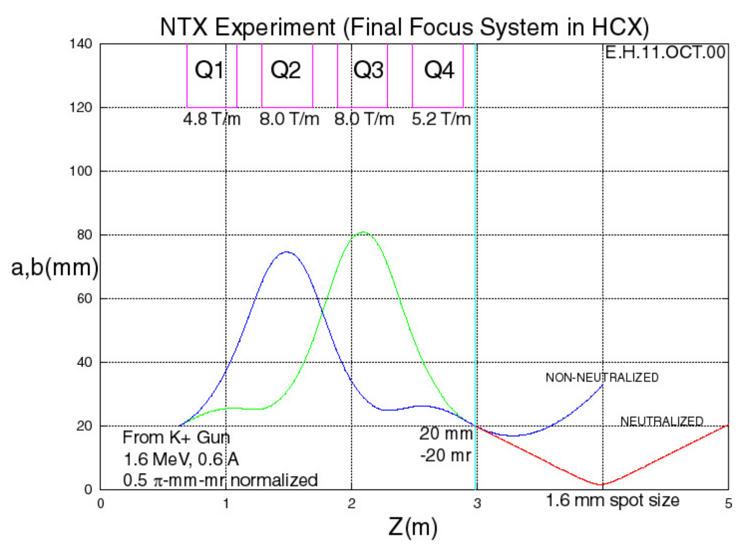


The PPPL ECR plasma source…



New source/optics in existing 400 kV injector allows low aberrations and small focal spots after neutralization, for a range of beam space potential $\Delta\phi$ to ion energy E_{ion}

→large plasma neutralization effect



…will allow control of both spatial plasma gradient as well as a range of plasma to beam density ratios, with very low background gas.

The HIF-VNL Effort FY01 and proposed FY02-03

Year	Guidance case, flat ($K)			Request case, enhanced		
FY01	LBNL/LLNL	PPPL	VNL	LBNL/LLNL	PPPL	VNL
Staff	22/15	5.3	43.9			
Operating	4489/4500	1090	10079			
Equipment	499/0	38	537			
Total	9488	1128	10,616			
FY02						
Staff	22/15	5.1	42.1	28/19	8.2	55.2
Operating	3900/4500	1130	9530	5500/5400	1620	12,520
Equipment	1100/0	0	1100	4000/0	0	4000
Total	9500	1130	10,630	14,900	1620	16,520
FY03						
Staff	22/15	5.1	42.1	28/21	8.2	55.2
Operating	4500/4500	1130	10130	5600/5800	1620	
Equipment	500/0	0	500	4000/0	0	
Total	9500	1130	10,630	15,400	1620	17,020

Distribution of VNL effort towards FESAC 5 yr objectives

Across: 5-year objectives (from FESAC Knoxville IPPA Reports) **Down:** **HIF-VNL scientific issue**	6 . 1 Heavy Ion Beam Experiments and Supporting Accelerator Tech.	6.2 Integrated Ion Beam Modeling, Focusing and Transport	5.1 Beam Target Interaction and Coupling
(1) beam brightness in heavy-ion sources	30%		
(2) dynamical phenomena in transport and acceleration	30%		
(3) non-linear processes in chamber propagation/focusing		5%	5%
(4) computational tools		25%	5%

Plans for FY02 and FY03, if flat VNL budget at $10.6 M/yr

- **FY02**
  - Complete HCX transport experiments with ~ 40 electric and 4 existing magnetic quadrupoles
  - Complete simulations of the initial HCX transport experiments
  - Understand and characterize brightness of multi-aperture plasma sources
  - Begin 100 mA beam-plasma neutralization experiments
  - Optimize BEST code, assess beam-plasma instabilities, complete model for beam compression dynamics and nonlinear beam optics.
- **FY03**
  - Add a few hundred kV of induction acceleration to tailor the head and tail of the HCX beam
  - Test merging beamlet injection on the 500 kV test stand.
  - Complete 100 mA beam-plasma neutralization experiments.
  - Complete end-to-end simulations of the HCX, merging beamlet, and beam neutralization experiments
  - Complete assessment of optimum beam/chamber conditions for focusing. Complete equipment for multielectron loss experiments on GSI-scale facility.

Changes to FY02 and FY03 efforts if VNL budgets +or- 10%

If VNL budget were down 10% (to $9.54 M for FY02 and 03)

- Limit HCX transport to 40 electric quads and existing 4 magnetic quads: no acceleration or procurement of superconducting quadrupoles. Lose Phase II design effort (severely limits future productivity).
- Reduce effort on high brightness ion sources
- Reduce scientific staff by 10%.
- Slow multielectron loss work.

If VNL budget were up 10 % (to $11.7 M/yr for FY02 and FY03)

- Add new induction modules with active-waveform control to HCX, which would be prototypical of modules for acceleration in HCX.
- Design and procure a new higher current/brightness injector for HCX.
- Develop and apply massively parallel versions of WARP for end-to-end beam simulations.
- Increase pre-ionized plasma formation R&D for the LBNL focusing experiment, and increase chamber transport modeling support.

Plans for FY02 and FY03, if VNL budget were $16.5M/yr

- **To get a complete picture of how well beam brightness can be preserved under acceleration and final focusing, we need to add > 10 MeV acceleration to HCX to allow tests of beam compression and final focus of high currents.**

- **Acceleration in HCX is essential to provide integrated beam experiments to be compared to end-to-end modeling, to provide higher confidence in IRE, and to show that heavy-ion IFE has the potential for much reduced ion particle and driver energy.**

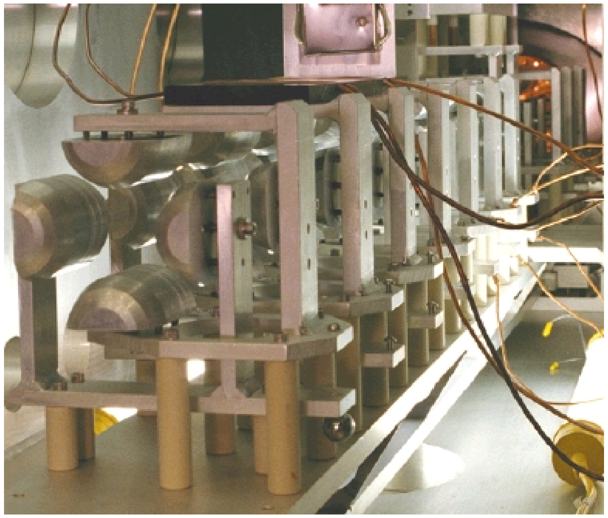
Summary

▪HIF-VNL science is aimed at finding the maximum beam brightness that can be produced and preserved under transport, acceleration and focusing, which will lead to the smallest focal spots.

▪A series of high current experiments and simulations are soon to begin which will improve our understanding of the limits to beam brightness due to non-ideal effects, and due to beam-plasma interaction near the focus.

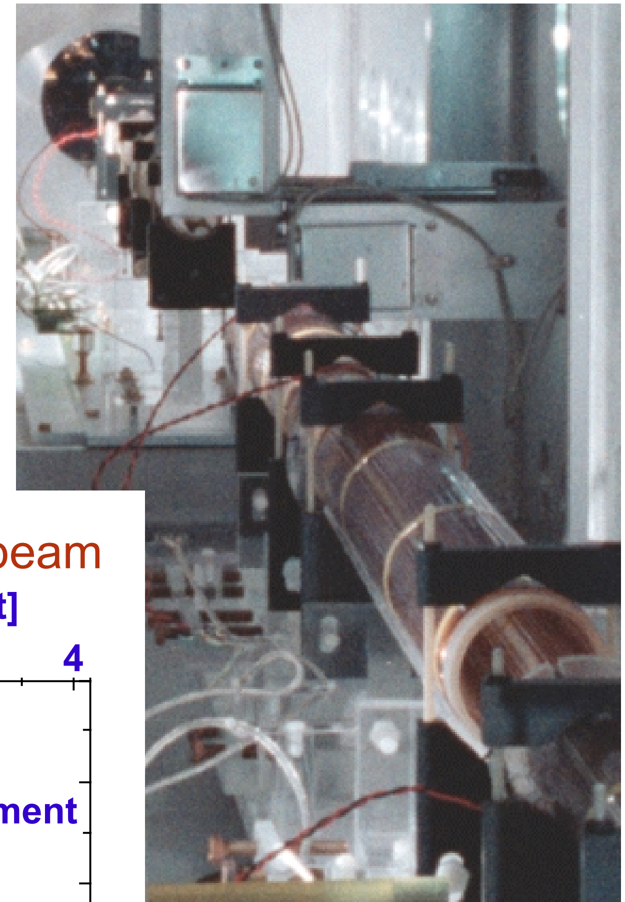
▪This research has the potential to make large reductions in the projected size and cost of heavy-ion accelerators for IFE

Final-Focus Scaled Experiment showed neutralizing electrons from a hot filament reduced focal spot

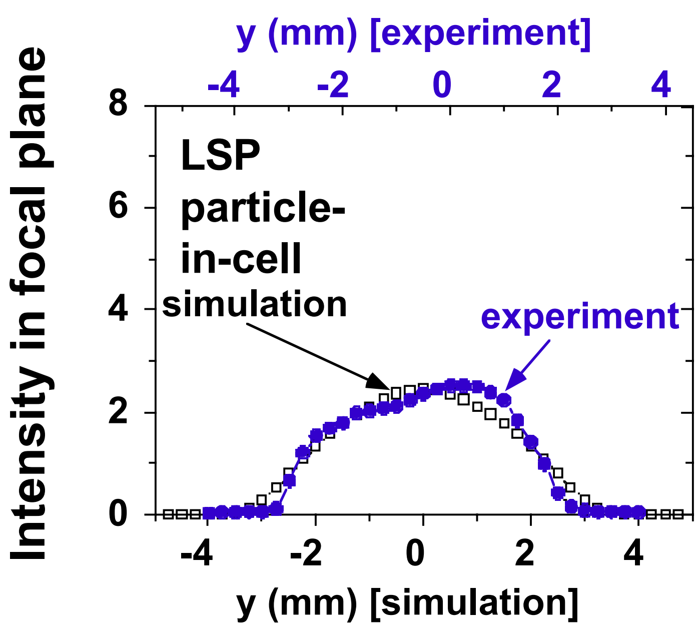


Electrostatic quadrupole lenses for beam set-up

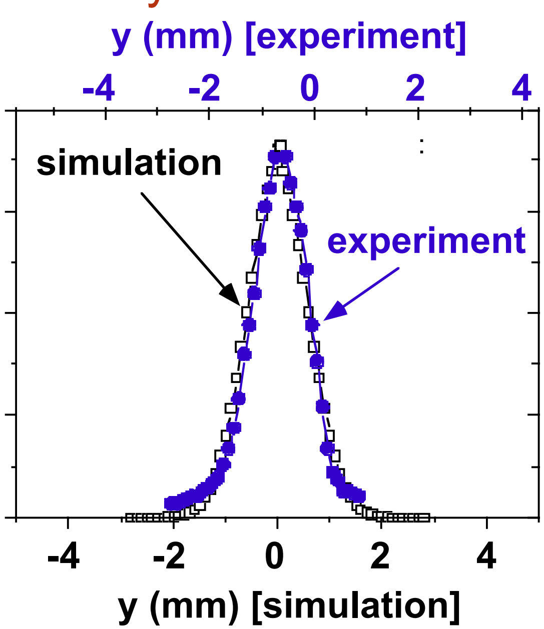
Magnetic quadrupoles for final focusing



Unneutralized beam

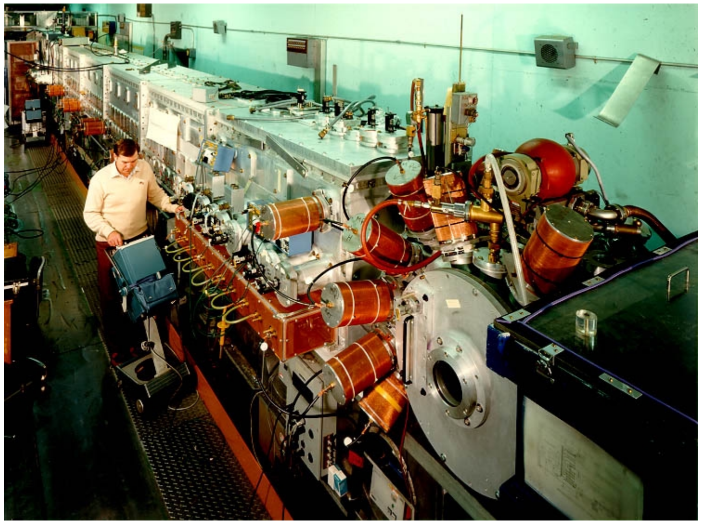


Partially neutralized beam



Scaled experiments at low current 400μA, 160 keV, Cs^+

Single-Beam Transport Experiment (SBTE)



10-20 mA
120 kV
86 electric quadrupoles
15 m long

Analytic theory previously suggested stringent limits on transportable current. Simulations using early supercomputers showed that the modes saturated at a low level, and this was later verified on SBTE.

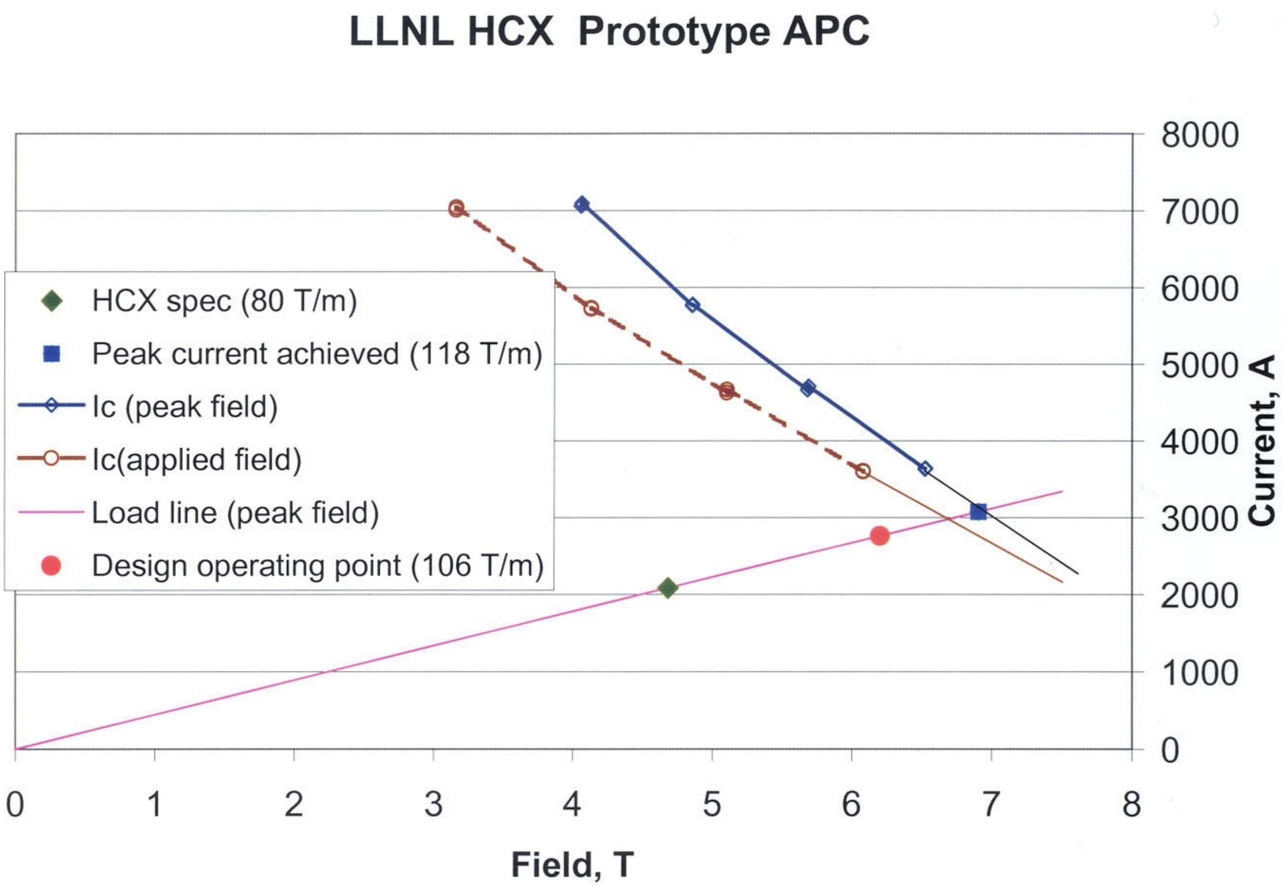
Multiple-Beam Experiment with 4 beams (MBE-4)

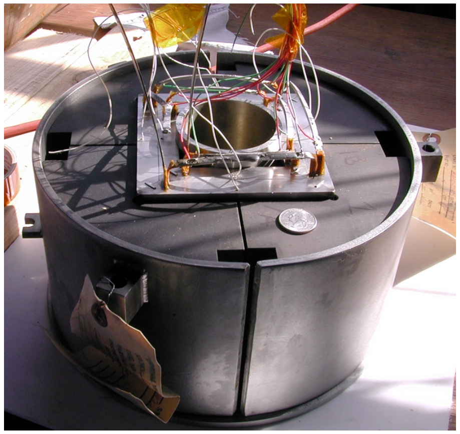
10-90 mA/beam, 200-900 keV

studied:

- acceleration
- current amplification
- longitudinal confinement
- multi-beam interactions
- phase-space dilution by collective effects

The LLNL HCX magnet has exceeded design performance for |B| after only 4 quenches





This magnet was designed by LLNL, built by a small San Leandro company, and tested at LBNL. Another design prototype will be tested at MIT.